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AIRBORNE INERTIAL BURST POWER SYSTEM

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TITLE: AIRBORNE INERTIAL BURST POWER SYSTEM

FOREWORD

This memorandum summarizes in-house work conducted by personnel of the Power Technology Branch (POOS), Aerospace Power Division (PO), Air Force Aero Propulsion And Power Lab (PO), Wright Research and Development Center, Wright Patterson Air Force Base, Ohio.

The work reported was conducted by the author, Charles Kessler (WRDC/POOS-1), during the period 18 December 89 to 12 February 90. The memorandum was released by the author in April 90. Appreciation is expressed to Mr. Gene Hoffman (WRDC/POOS-1) for his guidance on the project.

This document relies upon information derived from previously published technical data. It benefits those considering this type of energy storage device by explaining, in a concise form, the basics of system operation, mass penalties, and design considerations.

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1. INTRODUCTION

The development of airborne weapon systems presents the need for lightweight burst power sources capable of providing relatively high power levels for short time periods. The particular application considered here required the following:

* 250 kVA power level
* 10 second (baseline) burst period, 40 second maximum
* 2.5 Megajoule (baseline) stored energy
* houseability in C-130 aircraft wing pod
* quick recharge capability highly desirable

Excess aircraft power generation capability of approximately 60 kVA was not sufficient to supply the burst, so that additional power generation capability or an energy accumulation device was required. As the available power was sufficient to supply the average power load, a storage device was investigated.

The "mechanical capacitor" examined here is that of a rotating flywheel or inertial energy storage (IES) system which stores kinetic energy by virtue of its rotational speed. The application of this concept on an aircraft to provide burst power would be unique.

A relevant figure of merit for a flywheel is its specific energy density (SED). This quantity is the ratio of the energy stored by the flywheel at its maximum operating speed to its mass. System SED includes the mass of the motor, generator, support structure, and safety containment device (if feasible).

This document summarizes information gathered by the author while examining the feasibility of IES for this application. A detailed design was not generated and costs were not investigated.

2. CONCLUSIONS

The mass of the system required to fulfill the power needs mentioned above is approximately 147 Kg. This corresponds to a specific power density for the system of 1.7 KW/Kg and a usable specific energy density (SED) of 17 KJ/Kg. As a verification of these predictions, near-term estimates of 2.5 KW/Kg and 180 KJ/Kg system values were cited in the literature (Reference 1), which would imply that these estimates are conservative.

The system offers the following features:

* quick recharge capability allows high duty cycle
* AC output eliminates need for DC rectification
* potential mass savings
* specific power independent of specific energy
* design flexibility
* integration effort - no technology breakthrough required
* unlimited number of charge/discharge cycles
* long shelf life
* completely benign when not in operation
* volume efficient

3. DISCUSSION

3.1 MASS SUMMARY

The baseline system supplies 250 kVA for 10 seconds (2.5 MJ total energy) and recharges in 70 seconds for a maximum duty cycle (ratio of time at peak power to total time) of 12%. Figure 1 shows mass breakdowns for two baseline systems offering this performance. (The difference between the two systems is explained below.) Note from the figure that the flywheel itself does not drive the mass of the system, so that large mass penalties are not paid for increased safety factor or quantities of stored energy. The system is volume efficient, with all components fitting into a 4 ft by 2 ft by 2 ft space. A block diagram with relevant characteristics is included as Figure 2.

Figures 3 and 4 show trade-offs of recharge time and burst period against system mass. These charts are idealized in that no component inefficiencies are considered. To reduce recharge time, only motor power (and mass) must increase. To increase burst period (i.e., total stored energy), only flywheel mass must increase.

3.2 SYSTEM OPERATION

The system is very simple in theory. Available aircraft power drives a motor which spins-up the flywheel. The kinetic energy stored in the rotating body increases as the square of the speed. When the maximum operating speed (and stored energy) is achieved the "capacitor" is fully charged with sufficient energy to supply the peak demand. When output power is required, a 250 kVA generator is activated which delivers the accumulated energy over a short period. When the burst is over, the motor recharges the flywheel to its maximum operating speed and the system stores the energy until the next burst period.

3.3 COMPONENT SIZING

3.3.1 MOTOR

The baseline motor is a two-pole advanced permanent magnet design with a 50 HP rating. This is scaled from an existing machine of 45 HP at a power density of 1.1 HP/Kg. Increasing the motor power rating, and mass, reduces time required for recharging as was previously illustrated in Figure 3.

3.3.2 GENERATOR

The generator is a wire-wound synchronous machine scaled from a 40 kVA design using a power density of 6.6 KVA/Kg. This will produce a constant voltage, variable frequency output.

3.3.3 FLYWHEEL

The ideal specific energy density (SED) of a flywheel is calculated using the following relation (Reference 2):

EQN I:

$$\frac{E}{m} = K\frac{\sigma}{\rho}$$

Here, "K" is a non-dimensional geometric factor determined solely by cross-section. "σ/ρ" is the ratio of maximum allowable working stress to density of the material and is determined solely by the material.

This relation can be applied directly only for isotropic materials. For non-isotropic materials, the "σ/ρ" ratio which corresponds to the appropriate critical stress direction (radial or tangential) must be chosen.

This ideal SED cannot be achieved. It must be derated by a safety factor. Also, a synchronous generator will drop in frequency as the speed of the flywheel drops during energy extraction, so that only a portion of the stored energy is actually usable. In this application, the flywheel will spin-down to seventy percent of its maximum value so that one half of the stored energy is usable. These factors contribute to an actual flywheel SED which is twenty five percent of the ideal value.

As illustrated above, the flywheel SED is based on a geometric factor and a material factor. To bracket the flywheel mass required to store the necessary energy, these factors are bracketed. A generic "low tech" and "high tech" flywheel were considered. The low tech flywheel is an 18 Ni (300) high strength steel in the geometry of a right circular disk with a central hole which would allow a shrink fit to a shaft. The high tech flywheel has an optimized shape, which increases the geometric factor, and is constructed of E-glass/epoxy composite material with a higher σ/ρ ratio. The flywheel would be bolted to the shaft via a flange to eliminate the stress concentration due to a central hole. Specific energy densities of the two were shown previously on Figure 1.

Figure 5 gives examples of geometric factors associated with different cross-sectional geometries. Table 1 (Reference 3) includes values of the ratio for several materials.

3.3.3.1 "LOW TECH"

The least complex design imaginable would be a solid steel disk with a central hole through which the shaft passes. For this case, K=0.3 and σ/ρ = 259 KJ/Kg. The ideal SED is :

$$\frac{E}{m} = 0.3\times259\frac{KJ}{Kg} = 78\frac{KJ}{Kg}$$

The derivation of Equation I. will be illustrated for the case of this geometry. The difference between this geometry and others is the expression for critical stress in the rotating body.

The speed at which a flywheel of this geometry can rotate without failure is limited by tangential stresses which increase as the square of the angular speed as given by the following equation (Reference 4):

$$\sigma_\theta = \frac{3+\nu}{8}\rho\omega^2(R_o^2+R_i^2+(\frac{R_i^2R_o^2}{r^2}-\frac{1+3\nu}{3+\nu}r^2)$$

where:

γ = Poisson's ratio
ω = angular speed
ρ = mass density
R_i = disk inner radius
R_o = disk outer radius
r = radial distance

For this geometry, this stress has its critical value at the perimeter of the center hole as given by the following equation (if the hole is assumed small):

EQN II:

$$\sigma_{max} = \frac{3+\nu}{8}\rho(R_o\omega)^2$$

Note that the quantity $R_o\omega$ is the linear speed at the edge of the disk.

The kinetic energy stored in a rotating flywheel is given by the following relation:

EQN III:

$$E = \frac{1}{2} I \omega^2$$

where:

E = stored kinetic energy
I = moment of inertia of flywheel about its spin axis
ω = angular speed

For the geometry considered here:

EQN IV:

$$I = \frac{1}{2} m R_o^2$$

Making the substitution of EQN IV into EQN III, using EQN II, and solving for the energy density, we see that

$$\frac{E}{m} = \frac{1}{3+\nu}\left(\frac{\sigma}{\rho}\right)$$

or

$$\frac{E}{m} = K\left(\frac{\sigma}{\rho}\right)$$

where

$$K = \frac{1}{3+\nu} = 0.3$$

3.3.3.2 "HIGH TECH"

The estimation of SED for this design is based on K=0.9 and σ/ρ = 726. KJ/Kg. The ideal SED is:

$$\frac{E}{m} = 0.9 \times 726 \frac{KJ}{Kg} = 653 \frac{KJ}{Kg}$$

The E-glass/epoxy was chosen as a conservative estimate of composite material capabilities. This has the advantage of a factor of 3 increase in geometry factor with a factor of 2.8 increase in σ/ρ for a total factor of 8.4 improvement over the "low tech" design. As evidence that this value is achievable, an ideal energy density of 878 KJ/Kg at burst has been demonstrated (Reference 3). As explained below, this calculation looks identical to the isotropic case but is actually not as straightforward.

For composite materials which are circumferentially wound, strength in the radial direction (matrix strength) is much less than that in the tangential direction (fiber strength). The specific material properties determine the failure criterion, so that more care is required in SED estimation than for isotropic materials. The radial stress may be smaller than the tangential stress, but the strength in the radial direction may be sufficiently small that this becomes the limiting stress.

A design approach is available which eliminates limitations imposed by a weak radial yield strength (Reference 5). If concentric rings are interference-fit to form the entire disk, each will be compressively prestressed. This approach allows the designer to tailor failure mode and radial location.

3.3.4 CONTAINMENT

The failure mode of a steel flywheel is such that a catastrophic failure is considered uncontainable. It is generally assumed that three equal fragments are formed at failure. A composite flywheel fragments to a much greater degree and can be contained for a modest mass penalty. The mechanism to contain the failure is a radial ring which deforms as the radial momentum of the fragments is absorbed. This is based on work which predicts a containment requirement of 4 Kg/MJ (Reference 5).

3.3.5 STRUCTURE MASS

Other components are required in the system the mass of which is more difficult to quantify. At high rotational speed, flywheels must operate in an evacuated environment to eliminate aerodynamic heating. The motor and generator require cooling systems. Mechanical support structure is necessary. The mass of these was included in Figure 1 as the "structure mass" category and is conservatively estimated as twenty five percent of the total mass of other components.

3.4 TRADITIONAL CONCERNS

Inertial energy storage has not been extensively used to supply airborne power. Several reasons for this are listed below.

3.4.1 SAFETY

The flywheel stores a large quantity of energy in a small space. This energy could cause much destruction in the event of a catastrophic failure. Safety is a very understandable concern.

The energy stored in the flywheel examined here is approximately twice the energy present in the rotating turbine and compressor disks of each of the aircraft's four engines. This is mentioned to make the point that other rotating machinery on the aircraft, not designed to do so, stores quantities of energy comparable to that required for this application. Design safety margins and periodic inspection ensure the safety of these rotating components. The approach of optimizing this rotating machinery for energy storage is not unrealistic.

There are several design approaches available to avoid a complete catastrophic failure. The flywheel outer rim can be designed to run very close to the housing so that increased radial strain due to creep or overspeed conditions will cause a braking action. A notch effect can be designed which will cause a small portion of the total mass to separate before a complete failure, which would signal a controlled shutdown.

An additional approach is available for composite designs (Reference 5). The flywheel can be designed so that the matrix fails in the radial direction before the circumferential fibers fail. This will generate a mass imbalance which can be sensed to signal a controlled shutdown while the fibers hold the wheel together.

3.4.2 MASS

Any existing operational IES units known to the author have used isotropic metallic flywheels and massive enclosure structures. If containment against catastrophic failure is required and a metallic flywheel is used, the system will be too heavy for use in an aircraft. Composite flywheels allow the system to be mass competitive.

3.4.3 GYROSCOPIC EFFECTS

The torque generated by precession about axes perpendicular to the spin axis is proportional to the angular momentum of the rotating body. The angular momentum of the flywheel considered here is approximately equal to that of the combined compressor and turbine disks of each of the four engines. Thus, the aircraft would experience twenty five percent additional torque if the flywheel spin axis was parallel to and in the same direction as those of the engines. The spin direction of the flywheel could be chosen to oppose that of the engines and actually reduce the gyroscopic torque.

A design option is available to eliminate the gyroscopic effect of the rotating flywheel. Two counter-rotating flywheels would theoretically cancel the effect generated by each other and precession would produce no net torque on the aircraft. The obvious disadvantage of this option is additional components which contribute to a lower overall system reliability.

3.4.4 HIGH SPEED ROTATING MACHINERY

No problems unique to this application of rotating machinery exist. A less harsh operational environment makes this a less complex problem than the design of engine components. The flywheel must be designed such that no critical speeds exist in the operating range. Accurate balancing would also be critical. Solutions to these problems represent straightforward application of mechanical engineering principles.

3.4.5 LOSSES

Losses during energy storage due to bearing friction and windage will occur. Available aircraft power, through the spin-up motor, can compensate for these. Bearing losses can be considered negligible (Reference 6). The following expression is valid to calculate windage losses for a right circular disk (Reference 6):

EQN V:

$$P_w = 2.04\times10^{-8}\left(1+2.3\frac{t}{R}\right)\rho^{0.8}\mu^{0.2}R^{4.6}n^{2.8}$$

where :

P_w = power loss due to windage (kW)
μ = viscosity of surrounding fluid (cP)
t = thickness of disk (meters)
ω = angular speed of disk (rpm)
R = disk outer radius (meters)
ρ = density of surrounding fluid (Kg/m^3)

For scaling purposes, a test rotor of 1.75 inch thickness and 9.0 inch radius dissipated approximately 9.0 KW at 15,000 RPM when vented to atmospheric pressure (Reference 6). A plot of this relationship assuming atmospheric pressure and identical air conditions is included as Figure 6.

The flywheel and motor and generator rotors would each contribute to total windage loss.

3.4.6 VACUUM REQUIREMENT

As shown by Equation V, no windage losses will occur in an absolute vacuum. Windage losses are manifested as heat which, among other things, raises the temperature of the flywheel material and lowers its mechanical properties. Thus, it is important to minimize these losses by operating the flywheel in a tight vacuum environment. This brings with it requirements for sealing and a vacuum source. Properties of composite materials degrade more rapidly with increasing temperature than do those of metals, making this requirement more critical.

4. EXAMPLES OF MANUFACTURED FLYWHEELS

An example of the application of this technology on an aircraft could be found in the literature, but for a much lower energy requirement. A form/fit/function replacement for a battery energy storage device was documented (Reference 7). The requirements for this system were 500 watts for 5 seconds, with 2.5 KJ total usable energy stored. The application was interim power for the AS/ASN-92 Carrier-Aircraft Inertial Navigation System (CAINS) during the transition from carrier-based to aircraft-based electrical support. Benefits noted included unlimited charge/discharge cycles, ease of state-of-charge monitoring, long shelf life, and much improved reliability.

A summary of demonstrated composite flywheel performance resulting from the Mechanical Energy Storage Technology (MEST) Program conducted by Oak Ridge National Lab can be found in Reference 3. The maximum flywheel SED achieved at failure is reported as 878 KJ/Kg. Several other designs were tested for 10,000 cycles from half-speed to maximum speed with no degradation observed. Operational flywheel specific energy densities of approximately 400 KJ/Kg were reported.

Conference proceedings of the Intersociety Energy Conversion Engineering Conference (IECEC) are an excellent source of data on current work in the inertial energy storage area.

5. SUMMARY

To summarize the findings of this study, the major advantages and disadvantages of an IES system are repeated below.

-ADVANTAGES

* quick recharge capability allows high duty cycle
* AC output eliminates need for DC rectification
* potential mass savings
* specific power independent of specific energy

* design flexibility
* integration effort - no technology breakthrough required
* unlimited number of charge/discharge cycles
* long shelf life
* completely benign when not in operation
* volume efficient

-DISADVANTAGES

* safety concern
* rotating machinery
* vacuum requirement

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